

Airborne Conflict Management within Confined Airspace in a Piloted Simulation of DAG-TM Autonomous Aircraft Operations

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Abstract

A human-in-the-loop experiment was performed at the NASA Langley Research Center to study the feasibility of Distributed Air/Ground Traffic Management (DAG-TM) autonomous aircraft operations in highly constrained airspace. The airspace was constrained by a pair of special use airspace (SUA) regions on either side of the pilot's planned route. The available airspace was further varied by changing the separation standard for lateral separation between 3 nm and 5 nm. The pilot had to maneuver through the corridor between the SUA's, avoid other traffic and meet flow management constraints. Traffic flow management (TFM) constraints were imposed as a required time of arrival and crossing altitude at an en route fix. This is a follow-up study to work presented at the 4th USA/Europe Air Traffic Management R&D Seminar in December 2001[1].

Nearly all of the pilots were able to meet their TFM constraints while maintaining adequate separation from other traffic. In only 3 out of 59 runs were the pilots unable to meet their required time of arrival. Two loss of separation cases are studied and it is found that the pilots need conflict prevention information presented in a clearer manner. No degradation of performance or safety was seen between the wide and narrow corridors. Although this was not a thorough study of the consequences of reducing the en route lateral separation, nothing was found that would refute the feasibility of reducing the separation requirement from 5 nm to 3 nm. The creation of additional, second-generation conflicts is also investigated. Two resolution methods were offered to the pilots: strategic and tactical. The strategic method is a closed-loop alteration to the Flight Management System (FMS) active route that considers other traffic as well as TFM constraints. The tactical resolutions are short-term resolutions that leave avoiding other traffic conflicts and meeting the TFM constraints to the pilot. Those that made use of the strategic tools avoided additional conflicts, whereas, those

making tactical maneuvers often caused additional conflicts. Many of these second-generation conflicts could be avoided by improved conflict prevention tools that clearly present to the pilot which maneuver choices will result in a conflict-free path.

These results, together with previously reported studies, continue to support the feasibility of autonomous aircraft operations.

Introduction

The NASA Advanced Air Transportation Technologies project is conducting exploratory research and development of a far-term concept of operations for Air Traffic Management (ATM) defined by a redistribution of ATM responsibilities between air traffic service providers and aircraft flight crews. The operational concept is called *Distributed Air/Ground Traffic Management* (DAG-TM)[2], and many of its elements proceed along the conceptual path offered by the original RTCA Free Flight concept[3] wherein flight crews select their path and speed in real time while conforming to restrictions established for safety and flow management. One of the DAG-TM concept elements[4] describes operations in the en-route and terminal-transition domains and establishes a clear delineation of responsibilities between the groundside and airborne participants within these domains, albeit representing a significant shift in responsibilities from current-day operations. The principal shift proposed in this concept is that properly trained flight crews of properly equipped aircraft can assume full responsibility for separation from similarly equipped traffic throughout the en-route and terminal-transition domains. Aircraft not in this category continue to receive separation services from the ground. The primary anticipated benefit of creating this new category of aircraft operations is the ability of the National Airspace System to accommodate a substantial increase in traffic volume over that manageable by a ground-based system. This scalability would result from minimizing the interactions between this new category of

“autonomous aircraft” and the ground-based air traffic service (ATS) provider. Not surprisingly, minimizing the interaction is the principal challenge of the concept development. The concept includes many features for this purpose, but a description of these features is beyond the scope of this paper[2],[4]. Assuming the interactions can indeed be minimized, it is possible to study the operations of autonomous aircraft in isolation from the operations of the ATS provider, provided the areas where interactions do occur are avoided or carefully handled.

Shifting responsibility for ensuring traffic separation of equipped or “autonomous” aircraft to the flight crew of such aircraft would change the nature of the separation assurance task. This transfer of responsibility would greatly reduce the pairs of aircraft that a single person or team would have to separate. Whereas the air traffic controller in current operations must ensure separation between each and every pair of Instrument Flight Rules aircraft in the sector, the flight crew of an autonomous aircraft must only be concerned with aircraft pairs that include itself. Therefore, distributing the separation assurance task among multiple flight crews subdivides the total required effort into what might be fairly minor additions to each flight crew’s activities.

The nature of the separation assurance task may be even further changed when one considers that flight crews can afford to take more time and evaluate more options than could an air traffic controller solving the same conflict. Since the flight crew maintains continual focus on their aircraft’s intended trajectory, rather than intermittent focus, they can opt to resolve traffic conflicts earlier or later, and they can monitor the situation as it develops. They can also take time to consider more alternatives for implementing a resolution maneuver, be it a tactical resolution that involves continual maneuver decisions and monitoring, or a strategic resolution through a one-time modified Flight Management System (FMS) route that may include simultaneous achievement of multiple objectives and little monitoring. A recent piloted simulation of tactical and strategic modes for autonomous aircraft operations found that both modes are consistent with and support feasibility of the DAG-TM concept[1],[5].

With fewer aircraft pairs to consider for separation assurance, greater time and flexibility to solve conflicts, and the ability to monitor developing situations more closely, flight crews of autonomous aircraft may be able to readily manage flight through environments that might otherwise be considered highly constrained and challenging. Two factors that create such environments are the focus of the current study, and they contribute to a common effect, the proximity of hazards to the ownship aircraft.

The first of the two factors is airspace availability. Autonomous flight through wide-open airspace has been well studied, and no impediments to feasibility have been found for operations in this environment[6],[7]. The presence of airspace constraints such as special-use airspace (SUA) and convective weather reduces the maneuvering degrees of freedom for ensuring traffic separation and may therefore affect the willingness of air traffic controllers to

run significant traffic flows through these regions. The effect of highly confined airspace on autonomous flight operations is of interest because of the changed nature of the separation task described earlier. The greater flexibility and reduced task load afforded by airborne conflict management may permit flight operations in a more constrained environment with minimal impact on acceptability.

The second factor affecting hazard proximity involves the possible reduction in lateral separation requirements. In current operations, the minimum lateral separation requirement in en-route airspace is generally 5 nautical miles (nm). This standard is based in historical inaccuracies of long-range radar and resolution of air traffic controller displays. With the advent of accurate surveillance based on satellite navigation and digital data link, the possibility exists for safely reducing the required lateral separation minima. A multitude of issues related to the safety of reducing the separation standard exist, and the current study intends no recommendation to do so. Rather, this study offers a preliminary look at some isolated impacts on conflict resolution trajectories and pilot use of the extra airspace afforded by a reduced separation requirement.

The experiment reported herein addressed the issue of hazard proximity in a human-in-the-loop simulation of autonomous aircraft operations. This exploratory study attempted to determine operational effects of significantly reducing available maneuvering airspace and reducing the required minimum lateral separation between aircraft. It also attempted to characterize safety issues regarding the interaction between these variables. The experiment was performed in the NASA Langley Research Center’s Air Traffic Operations Laboratory, a distributed desktop simulation of aviation operations in which pilots of multiple simulated aircraft can interact in preplanned scenarios using prototype decision support tools and procedures under development for DAG-TM operations.

Confined-Airspace Conflict Scenario

The basic experimental scenario is motivated by a current airspace configuration in the area of Reno, Nevada, USA and is depicted in Figure 1. An autonomous aircraft, piloted by a single subject pilot, must traverse the corridor between two SUAs and meet arrival time and altitude constraints at an en route waypoint. In addition to the SUAs, the airspace is populated with other aircraft traveling in both directions through the corridor at altitudes above, below, and equal to that of the subject pilot’s aircraft. As with today’s operations, a cylindrical region of protected airspace, which must not be penetrated by any other aircraft, surrounds each aircraft. The independent variables studied are the width of the corridor and the lateral dimensions of this protected zone. The primary research issues studied are the interactive effects of required lateral separation and constrained airspace on a pilot’s ability to maintain separation and meet assigned constraints. Secondary research issues include safety of the flight operations through the corridor, acceptability and usability of the

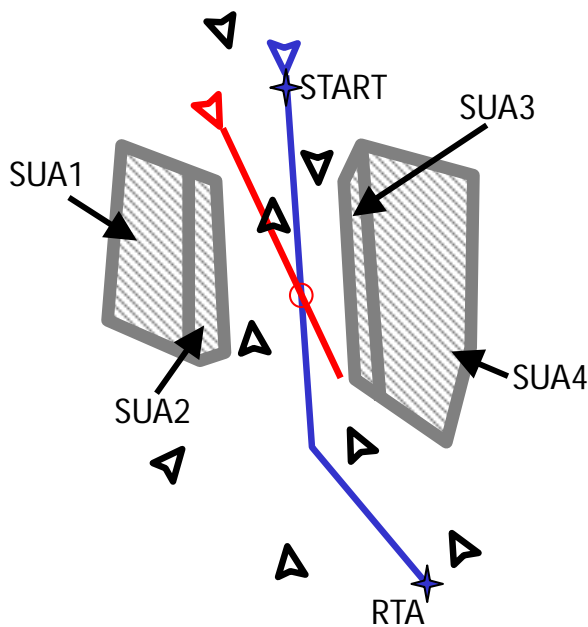


Figure 1: Basic Experimental Scenario

cockpit tools provided, and the utility of combined strategic and tactical resolution tools.

For purposes of this experiment, it is assumed that the ATS provider established the traffic flow management (TFM) constraints prior to the start of the scenario. They are pre-loaded into the subject pilot's FMS at initialization of the scenario. The waypoint constraints include a Required Time of Arrival (RTA), a "CROSS AT" altitude clearance and a requirement to over fly the waypoint. Crossing the RTA waypoint within 30 seconds of the assigned time, within ± 500 feet of the assigned altitude, and within ± 2.5 nm laterally is defined to be acceptable conformance to the TFM constraints. Subject pilots are provided an advanced suite of cockpit decision support tools and cockpit displays to help them satisfy their constraints. The purpose of the constraints is to provide quantifiable metrics against which the effectiveness of these cockpit decision tools and displays can be evaluated and to provide mission goals for the subject pilots.

The combination of active SUAs determined the amount of available airspace in each data run. Two conditions are studied: a narrow corridor and a wide corridor. The narrow corridor is created when all SUAs are active. It has a minimum corridor width of approximately 33 nm. The wide corridor is created when SUA 2 and SUA 3 are deactivated, freeing additional airspace for maneuvering. The minimum width of the wide corridor is approximately 65 nm. For data collection flights through the wide corridor, additional traffic aircraft are added to the simulation to maintain the aircraft density and, hence, the difficulty of the conflict avoidance task. Each flight occurs in either the narrow or the wide corridor. Subject pilots flew both conditions as part of the experiment design.

The second independent variable studied is the lateral dimension of the protected zone surrounding each aircraft.

Again, two conditions are studied: a zone with a 3 nm radius and a zone with a 5 nm radius. Each data collection flight involved only one of these conditions. Subject pilots were briefed on the zone size in effect prior to each flight. In all cases, the vertical dimension of the protected zone is ± 1000 feet. Reducing the lateral dimension of the protected zone effectively lowers the probability of conflicts with other aircraft and provides additional maneuvering freedom while maintaining the same corridor dimensions. In this experiment, it is the interactions between the airspace available and the dimension of the protected zone that are of interest. This experiment should not be interpreted as supporting a reduction in the current lateral dimensions of an aircraft's protected zone as many other challenges, such as accuracy of surveillance systems, exist that were not studied here.

At initialization of the scenario, the subject pilot's aircraft is established on a flight plan that meets all constraints at the RTA waypoint and the autoflight system is fully engaged. There are no conflicts between the initial active route and any of the SUAs. Unbeknownst to the subject pilot, there is one planned conflict between the active route of the subject pilot's aircraft and one other aircraft. However, the subject pilots are not constrained to follow the initial flight plan. Rather, they are advised to make their own best judgments regarding the conduct of the flight. The pilots are free to choose the lateral and vertical path that they feel best meets their objectives. Flights are *not* constrained to the hemispherical altitude flight levels. Therefore, it is possible for subject pilots to encounter unplanned conflicts and flight situations.

Regardless of their actions, subject pilots are aided by decision support tools and advanced cockpit displays that provide, among other services, automated conflict detection and resolution and multilevel alerting. These flight deck tools are being developed by NASA to support future civil operations under the DAG-TM paradigm. A principal component of this toolset is the Autonomous Operations Planner (AOP)[8]. The crew interacts with the AOP to perform trajectory planning that accounts for (1) conflicts with traffic hazards; (2) aircraft performance limitations; (3) TFM constraints; (4) airspace constraints, such as severe weather; and (5) operator flight goals, such as efficiency and schedule. The AOP manages information received by the flight deck from several sources and handles any redundant or ambiguous information. These sources include the direct broadcast of position and intent information from other aircraft in proximity, ground-based traffic information services, and ground-based flight information services.

As the scenario unfolds, the onboard automation alerts the subject pilot to any conflicts and presents possible conflict resolution trajectories. Subject pilots may elect to implement one of the suggested resolution trajectories or choose another resolution strategy. The alerting scheme employs a multi-stage alerting logic that increases the severity of the alert, as the time to conflict grows shorter. The RTCA Airborne Conflict Management (ACM) working group of Special Committee 186 developed the basis of

this alerting strategy[6]. The alerting logic combines both flight plan and state vector data that is broadcast from proximate aircraft. A conflict occurs anytime the flight plan or projected flight path of one aircraft penetrates the protected zone of another. For situations where both aircraft are in conformance with their broadcast intent, AOP probes them ten minutes ahead looking for conflicts. When the intent information is not accurate, AOP relies on a state-only system that has a five minute look-ahead[6].

For this experiment, the AOP and the display logic are configured to produce 4 levels of alerting. A level 0 alert is for an aircraft that AOP considers a possible, but not current, threat to the ownship. The display logic used a threat-based filtering system to de-clutter the display. Only aircraft satisfying at least the level 0 alert are displayed. A level 1 alert signifies a long-range conflict and corresponds to the ACM group's definition of a "low level alert." Pilot action is suggested but not required for a level 1 alert. A level 2 alert means the conflict is closer in time and the crew must take timely action to resolve the conflict. This corresponds to the "conflict detection zone alert" of the ACM group. A level 3 alert is decoupled from the previous ones. It is used in the case where a near collision, passing within 0.15 nm and 300 ft of another aircraft, is less than one minute away. This would be the final alert before a TCAS warning. The ACM group defined this as a "collision avoidance alert." The level 0 alert will not necessarily become a level 1 alert. A level 1 alert *will* upgrade to a level 2 if neither crew takes action. Most level 2 alerts will not become level 3 as the aircraft are not necessarily on a collision course. Note that there is no right-of-way system in place in the alerting and display logic.

Subject pilots receive two types of conflict resolutions: strategic and tactical. Strategic resolutions are useful for resolving potential conflicts at long range, for planning, and for maintaining conformance with TFM constraints. Strategic resolutions are computed by comparing the subject pilot's intended route of flight, as entered into the FMS, with trajectory intent data received from proximate aircraft. These data are in the form of trajectory change points received through an Automatic Dependent Surveillance-Broadcast (ADS-B) broadcast. An ADS-B data link simulation model determines the range at which the subject pilot's aircraft is able to receive data from proximate aircraft. The AOP uses all known traffic, weather and restricted airspace data to develop modifications to the subject pilot's flight plan that result in a new conflict-free trajectory for a pre-defined time into the future. This new trajectory is made available to the pilot as a modified route in the FMS. If the pilot elects to implement the new trajectory, it becomes the FMS active route. Subject pilots are provided means to accept, reject, or request new strategic resolutions whenever a conflict exists and they are in conformance with their FMS active route. The AOP continuously scans the FMS active route for any intent-based conflicts.

Tactical resolutions have advantages in near-term conflicts where avoidance of the conflict is the primary goal

and other objectives are secondary. By not considering objectives beyond minimal traffic avoidance, tactical resolutions can be computed and implemented much more quickly. Tactical conflict detection involves projecting the state vector (ground speed, track and vertical speed) of the subject pilot's aircraft forward in time and analyzing the projected trajectory for conflicts with similar state vector projections from proximate aircraft. Again, an ADS-B data link provides the exchange of state data for aircraft within reception range of each other. Using techniques pioneered by the National Aerospace Laboratory of the Netherlands[6], the AOP analyzes these state-projection trajectories for state-based conflicts and generates conflict prevention bands and tactical resolutions that appear on the subject pilot's displays. Tactical resolutions are recommended track and vertical speed changes. There is no effort made to return to the flight plan. Conflict prevention bands indicate no fly zones in terms of the aircraft heading and vertical speed that would result in a conflict. Tactical resolutions maneuvers are presented to the pilot during level 2 and higher alerts.

Strategic and tactical resolution strategies are complementary. Each address shortcomings of the other and both strategies will likely be successfully implemented in the future airspace. However, the consequences of implementing strategic versus tactical conflict resolutions can be very different. This investigation seeks to identify when pilots used the two different resolution tactics and the usefulness of the information presented to them.

Experimental Approach

This experiment was conducted as one branch of a larger simulation that addressed general issues related to traffic conflicts and hazard avoidance under the DAG-TM paradigm. The simulation design permitted multiple research issues to be investigated concurrently by utilizing a common baseline configuration for all research branches. Each branch investigated a particular conflict type or conflict geometry. This investigation focused on conflict management when the airspace available for maneuvering was constrained. Results of the other research branches will be reported at this conference and elsewhere. For this investigation, the hypotheses were: (1) Reduced lateral separation requirements would lead to fewer detected conflicts. (2) Corridor width and reduced lateral separation requirements would have little effect on RTA conformance.

Each research branch was conducted as a human-in-the-loop study utilizing sophisticated desktop flight simulators. For this investigation, the desktop simulation was configured to represent a modern "glass cockpit" flight deck augmented with DAG-TM tools and services for operations in a future airspace. Each simulation station provided subject pilots with fully functional attitude, navigation, and engine displays; a flight management system operated through a control display unit interface; a functional mode control panel; and an autopilot system. Subject pilots controlled the aircraft through inputs to the

autoflight system and could not “hand fly” the aircraft. DAG-TM displays and controls were fully integrated into the cockpit environment (e.g. alerts and resolutions appeared on the primary flight displays). Interactions with the ATS provider and intra-aircraft voice communications were not included in the simulation. For this investigation they were not needed since the TFM constraints were pre-loaded into the FMS prior to the start of each flight and voice communications, particularly between subject pilots, was not desired. It is assumed that air-to-air voice communications is not a requirement for successful autonomous flight.

Sixteen active or recently active airline pilots served as subject pilots. They were arranged in groups of 4 pilots each. Each group participated in 2 full days of training and data collection. Each pilot received group and individual training on the DAG-TM elements of the simulation and was given structured “hands-on” practice time with the simulator and the DAG-TM tools. The training covered DAG-TM procedures, alerting levels, and use of the conflict management tools. Printed materials, classroom briefings, one-on-one instruction, and hands-on practice were all utilized during the training. The four pilots flew simultaneously in the simulation. For this investigation, they did not interact with each other. The test matrix was a 2 X 2 matrix with the following independent variables: width of the corridor (narrow or wide) and lateral dimension of the separation zone surrounding each aircraft (3 or 5 nm). Each subject pilot flew all test configurations so the experiment utilized a “within subjects” design. The data collection flights were embedded in a larger test matrix that was counterbalanced for order of scenario presentation and for order of research issue. Subject pilots flew a total of 10 research flights during their visit. Four of the 10 flights were devoted to this investigation so each pilot flew all combinations in the test matrix once. Therefore, 16 data collection flights were conducted for each of the four cells of the test matrix. Due to simulation faults, data from five of the runs were unusable leaving 59 runs for analysis.

Each data collection flight began at a location outside the corridor formed by the SUAs that was approximately 200 nm from the RTA waypoint and lasted about 25 minutes. Subject pilots were instructed that safety of flight was their top priority and that meeting TFM constraints was an important but secondary objective. A moving map display depicting the location of the RTA waypoint, a current prediction of the arrival time error at the waypoint, and an autoflight system with RTA-meeting capability were provided to assist pilots in meeting the constraints. Prior to the flight, pilots were briefed which lateral protected zone dimension was in effect. This was necessary since the size of the protected zone affected the conflict detection characteristics and the zone radius could be determined from the navigation display. The subject pilots were not briefed that each flight included one planned conflict with another aircraft. Flight details (e.g. call sign, tracks of proximate traffic) were also changed from flight to flight to further disguise the basic scenario.

A “distraction” task was added to the subject pilot’s responsibilities to represent normal cockpit duties not replicated in the simulation. Every 90 seconds the subjects were asked to answer a simple aviation or trivia question that appeared in a separate window on the computer screen. All non-piloted traffic aircraft were flying scripted routes and did not maneuver to resolve conflicts.

Subject pilots received assistance from the DAG-TM strategic and tactical tools and from the autoflight system throughout the data collection flights. They were advised to use their “best judgment” to conduct the flight as they would during normal airline operations and to use the tools to support their flight decisions. They were instructed that “company policy” was to accept the strategic resolution if it seemed appropriate. However, current simulation capabilities limit the strategic resolutions to lateral path stretch maneuvers. No strategic vertical resolutions were provided even though more efficient vertical maneuvers were often possible. Subject pilots had complete freedom to implement any maneuver at any time and to change the FMS route to the RTA waypoint. If the FMS lateral, vertical and speed flight modes were fully engaged, the AOP produced a strategic resolution to any conflict based on the current FMS route. If it was not fully engaged, only tactical resolutions were available. Subject pilots could also implement a resolution of their own choosing. Therefore, it was possible for pilots to implement strategies that failed to meet the assigned constraints. If pilots determined that they would be unable to meet one or more of the waypoint constraints, they were instructed to notify ATS as early as possible. Since the simulation had no ATS component, pilots were provided three buttons to indicate which constraint(s) they would not be able to meet. This was briefed as the initial step in a data linked transmission that would result in the assignment of new TFM constraints.

To test our hypotheses and verify safe conduct of flight, we will investigate three major metrics: (1) the number of separation violations with either traffic or SUAs; (2) conformance to constraints; (3) types of avoidance maneuvers used; and (4) number of detected conflicts. Extensive data were recorded from which the states and tracks of all aircraft in the simulation plus all subject pilot inputs can be recreated. In addition to the simulation data, post flight and post experiment questionnaires were completed by the subject pilots which probed their assessments of the DAG-TM tools, the reasons they made certain flight decisions, and their assessment of workload. One-on-one and group debriefs were also conducted to gain additional feedback on DAG-TM operations and the simulation environment.

Preliminary Results and Discussion

Four metrics were identified above for investigation. First among these was to identify separation violations and SUA penetrations. Due to the limited amount of available airspace and the high level of nearby traffic, there were few safe and efficient trajectories from which the pilots could choose. A related parameter is the pilot’s comfort

level with the operation. If pilots are uncomfortable with a flight operation, they are often reluctant to fly it even if the operation can be performed safely. Several questions were asked of the pilots following each data run to elicit their opinions. The second metric measures the pilot's ability to conform to the TFM constraints. It is seen that the ability of the pilots to fly safely and efficiently is closely related to the avoidance maneuvers they made (the third metric mentioned above); therefore, we will discuss the different resolutions methods implemented. The final metric looks at the number of additional conflicts created beyond the scripted ones.

Overall Safety and Acceptability of Operations

The pilots were asked to meet several constraints during each experimental run: maintain legal separation (either 3 nm or 5 nm laterally and 1000 ft vertically); stay outside the restricted airspace (SUA); and meet traffic flow management constraints (a required time of arrival and crossing altitude downstream). In addition, their "company" required them to consider fuel and time efficiency along with passenger comfort (i.e., gentler maneuvers were preferred to more aggressive maneuvers).

In general, we found that the pilots were able to maintain the required separation and meet their TFM constraints. There were three cases where the pilot failed to maintain the required separation. However, we feel that none of these were violations that compromised safety, but rather were minor, technical infractions; in fact, one was the direct result of a simulation shortcoming and not the pilot's actions.

In the first violation case, the pilot allowed his primary conflict to develop for several minutes to the point where he needed to take timely action to avoid a separation violation. He failed to check the conflict prevention system before initiating a climb that took him into the protected zone of an aircraft passing 1200 ft overhead. The pilot quickly stopped his climb, leveling off 800 ft below the other aircraft. The pilot was already behind the other aircraft, traveling slower and on a divergent trajectory. The subject pilot maintained course allowing the event to slowly improve until separation was regained.

The other two violations occurred to another pilot during one data run. In his first violation the pilot had climbed 1000 ft to solve his primary conflict. As he passed overhead of the other aircraft he preset his MCP altitude back to his desired altitude but did not engage the maneuver. He stayed this way for several minutes until he was comfortable that the other aircraft was outside the five nautical mile range necessary. He started his descent a few seconds too early and clipped the edge of the separation zone. The pilot failed to use a tool provided that would have shown the other aircraft's separation zone shown on his CDTI. This would have helped him ensure he had gained adequate separation before starting his descent. A similar situation occurred later in the same run. This time the subject pilot was climbing to a new altitude. He had set a target level off altitude and using the conflict prevention system, chose a vertical speed that would make sure he would avoid an aircraft passing directly overhead and

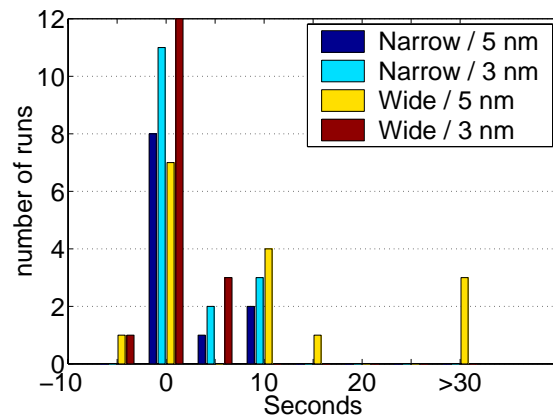


Figure 2: Time off Required Time of Arrival (RTA). Bins are 5 seconds wide.

headed in the opposite direction. As he approached the target altitude the autopilot system in the simulator overrode his selected climb rate causing the aircraft to climb more steeply. This was clearly the responsibility of the simulator software and not of the pilot. He had showed by his slow climb that he understood the situation and felt in control. He penetrated the trailing end of the other aircraft's protection zone. The entire event lasted only a few seconds before separation was regained.

None of the separation violations seriously compromised safety. However, the two operator error cases show that additional work must be done to ensure the safety of autonomous flight, particularly when the pilots make vertical maneuvers.

The subject pilots did nearly as well on meeting their TFM constraints. Out of the 59 data runs, three pilots failed to meet all three of their TFM constraints. These three pilots met the fix and altitude constraints but arrived more than 30 seconds behind their assigned times. In fact, the rest of the pilots arrived within 15 seconds of the assigned time and 43 of those were within five seconds (see Figure 2). The initial speed of the aircraft, which would have satisfied the constraints if no maneuvering were required, was approximately 15 KIAS (0.06 Mach) below the performance limits of the aircraft for the assigned altitude. This allowed for some speed adjustment over the course of the 25-minute scenario to account for possible delays. Neither the method that the pilot chose to resolve the primary conflict (tactical or strategic) nor the geometric plane of the maneuver had an observable effect on how well they could meet the constraints. One of the pilots received a bad strategic resolution that caused the missed RTA and the other two tried modifying their strategic resolution and ended up making several additional maneuvers.

After each data run, each pilot was asked three questions concerning their comfort level and acceptability of the flight. Responses were on a seven-point scale with high numbers being more comfortable/acceptable. Under all four conditions the median responses were between 6 and 7 showing the pilots' deemed this type of highly con-

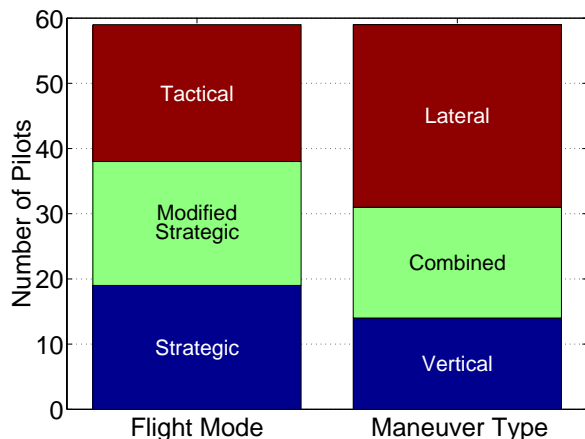


Figure 3: Breakdown of flight mode and maneuver type for conflict resolution.

strained operations acceptable and viable.

Resolution Methods

A well-designed decision support tool should present flight guidance that conforms to the pilot's methods of flying. Therefore, the development of such a tool is necessarily an interactive process with substantial feedback from the users. A good support system would improve the decisions made by pilots as well as make them feel comfortable with their decisions. No matter how sophisticated the tool becomes, it is the pilot who is the ultimate decision maker and not the technology.

In this experiment the pilot's conflict resolution strategies are classified as strategic or tactical, as discussed above*. Several pilots also used a modified strategic resolution where they accepted the strategic resolution but then modified it tactically. This was sometimes a result of a new decision as to how to resolve the conflict and sometimes a result of trying to improve the resolution that had been offered.

The direction of the resolution maneuvers was categorized as lateral, vertical or a combination. A speed change on its own was generally insufficient to resolve a conflict in these scenarios; therefore, we do not count speed changes as resolution maneuvers. Few pilots made simultaneous heading and altitude changes but several maneuvered separately in each direction; e.g. a heading change followed a few minutes later with an altitude change. These are the maneuvers classified as combined. Figure 3 shows both the resolution mode used and the maneuver type. It is clear that the pilots made use of all three resolution strategies and all available degrees of freedom.

The current implementation of the AOP is only able to offer lateral path stretch resolutions. Based on pilot comments, there is interest in having additional options for the strategic mode that would include vertical resolutions.

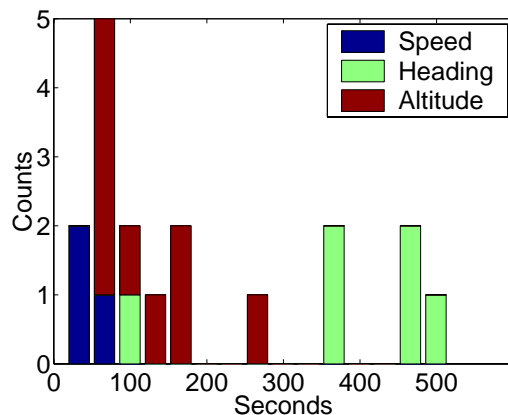


Figure 4: The time between the pilot accepting a strategic resolution and modifying it with a tactical maneuver. Maneuvers shown are the first maneuver after accepting the strategic resolution. Bins are 33 seconds wide.

Of particular interest to us are the pilots who initially accepted the AOP strategic resolution but later modified it. Figure 4 shows the direction of first modification by the pilot after implementing the strategic resolution. The maneuver types separate out very nicely based on time since acceptance. It appears that those who first altered speed did so because they wanted an added time buffer to meet their RTA. The speed adjustment was done within the first minute after accepting the resolution. Although the autoflight system would adjust the speed to maintain the RTA, several pilots expressed the desire to build an additional buffer early on to use in cases of a conflict late in the scenario.

The majority of alterations came from pilots who made vertical maneuvers in addition to the lateral, strategic resolution. About half of the pilots followed their altitude change with a turn back towards their RTA fix. They seem to have decided that a vertical resolution was a better choice than the lateral one offered. These maneuvers generally happened soon after the strategic resolution turned the aircraft off its initial flight plan. In the rest of the vertical alterations, the pilot stayed on the lateral path but added an altitude buffer. Since the separation zone is a cylinder, this maneuver earned them little additional separation but came at a cost in efficiency.

The final set of modifications was additional lateral maneuvering. Five of them occurred more than five minutes after accepting the initial resolution; around the time the ownship would have been passing near the conflicting aircraft. These were either maneuvers to shave the corner around the other aircraft or to alter the trajectory back to the original flight plan. The one lateral event near 90 seconds was of a different nature. As soon as the aircraft started to turn away from the initial flight plan the pilot decided to nullify the strategic resolution by turning back onto his original course. He later resolved the conflict by climbing over the traffic.

* See Ref. [1] for a more detailed description of these two modes of operation.

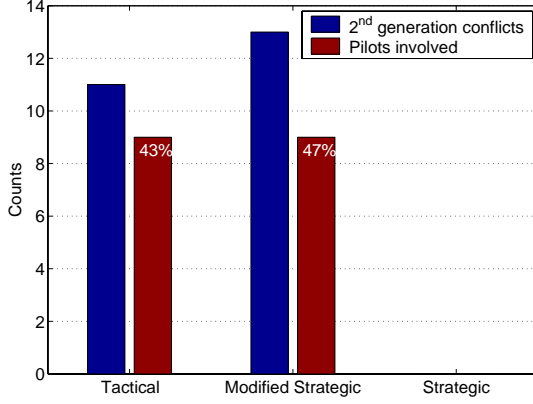


Figure 5: Second-generation conflict counts as a function of resolution strategy.

System Stability

A major goal in conflict resolution is to minimize the resolution's effect on other aircraft in the system. The reduction in additional conflicts adds stability to the system as a whole and localized conflicts will not grow to include additional aircraft.

In this experiment, special precautions were taken to ensure that there would be no conflicts save the one planned along the nominal flight plan. Therefore, all additional conflicts (we will call them second-generation conflicts[1]) occurred due to the pilot deviating from the nominal flight plan to avoid the planned conflict[†]. The strategic resolutions offered by AOP were ensured to be conflict free for the next 20 minutes. Conversely, the tactical resolutions did not take into account other aircraft besides the conflicting aircraft and the pilot was responsible for avoiding future conflicts. Figure 5 shows the distribution of second-generation conflicts across resolution strategies. We see that the strategic method caused no additional conflicts as was expected. The planned conflict occurred a few minutes into the scenario so the 20 minutes of clear space that AOP assured took the pilot nearly to the end of the scenario. The results between solely tactical resolutions and modified strategic differ only slightly. For the pilots using the modified strategic resolution method, all second generation conflicts occurred after the tactical modification.

There were a total of 26 second-generation conflicts in addition to the 59 planned conflicts. This is a conflict increase of 44%. This is noticeably higher than was found in previous work[1],[5] where there was 25-30% increase. Several factors help explain the increase. Approximately 10 of these conflicts occurred near the end of the data run, well beyond the area of the planned conflict. In most of these cases, the pilot maneuvered tactically while inbound to the RTA fix and came into an unplanned conflict that

[†] Multiple conflicts with the same aircraft are not counted as separate second-generation conflicts. These "failed resolutions" will be treated in a forthcoming paper.

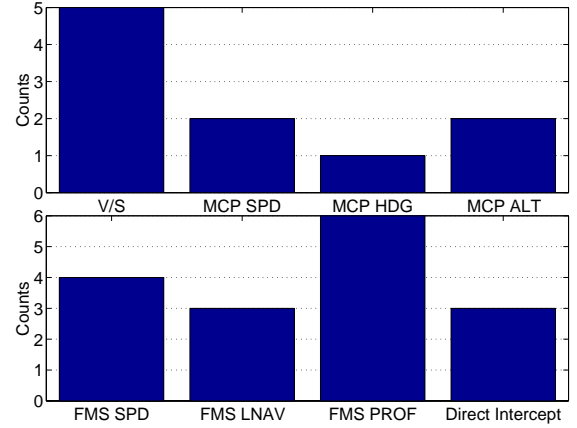


Figure 6: The last action performed by the pilot before a second-generation conflict was detected.

would not have occurred until after the data collection period was terminated. This was partly due to the limited look-ahead time of the conflict prevention system and partly due to the manner in which the conflict aircraft was introduced into the simulation. Removing these 10 late conflicts from consideration would have reduced the proliferation to only 14%.

The majority of second generation conflicts occurred in the runs with the 5 nm separation standard. During the 32 data runs with a 3 nm standard there were 6 second generation conflicts. In the 27 data runs that used the 5 nm standard there were 18 second generation conflicts. This difference is attributed to the larger avoidance area for the larger separation standard. A 5 nm standard removes almost three times as much airspace as the 3 nm standard.

One of the two pilot-caused loss of separation cases was a second-generation conflict. This was the first case described where the pilot ignored the conflict prevention system and climbed towards another aircraft. It is clear from these and previous results[1] that pilots often do not consider the vertical conflict prevention information before maneuvering. Improvements to the displays conveying this information are needed to make it more apparent.

There were three major techniques the pilots used to change their trajectory. The first was to make a change through their Mode Control Panel (MCP). The second was to engage an FMS mode that was not previously engaged. This could make a change to the actual trajectory or could just change the manner in which the trajectory would be flown and evaluated by AOP. Finally, several pilots made use of the Direct Intercept function in the FMS. This changes the FMS flight plan to go from the current position to the pilot selected fix further down the established flight plan.

Looking at the last action the pilot made before seeing the alert (Figure 6), there is a pretty even spread between tactical maneuvers and FMS changes that led to second-generation conflicts. In several cases, engaging the FMS caused an alert just by extending the look-ahead time. These conflicts would have eventually been detected at

the tactical time horizon, if the pilot had taken no action. The current conflict prevention system offers little guidance to the pilot as to when changing an FMS mode or performing a direct intercept would cause a conflict. The ability to test these changes before implementing them is currently under development for future versions of the AOP.

Conclusions

This work looked at the feasibility and acceptability of performing DAG-TM autonomous flight management in a highly constrained environment. In a desktop simulation of en-route autonomous operations, subject pilots were asked to negotiate a narrow corridor of airspace in the presence of other traffic and to meet en route flow management constraints. In each scenario, an aircraft was scripted to come into conflict with the subject's aircraft well into the passage through the corridor. The pilot had the assistance of the Autonomous Operations Planner, a developmental flight deck decision support tool, to detect traffic and airspace conflicts, propose resolutions and assist the pilot in avoiding additional conflicts. In addition to further investigating concept feasibility and acceptability beyond results from previous research, the hypotheses for this investigation were: (1) Reduced lateral separation requirements would lead to fewer detected conflicts. (2) Corridor width and reduced lateral separation requirements would have little effect on flow management constraint conformance.

We found that autonomous operations in this highly constrained environment are feasible. There were only a few failures to meet all constraints; none of them affected the safety of operations or the stability of the system. The reduced lateral separation requirements decreased the number of secondary conflicts by two-thirds. The pilot's ability meet the flow management constraints was not effected by the separation standard in use or the width of the corridor.

In a previous experiment[1],[5], significantly increasing traffic density (up to three times 1997 traffic densities in ZFW) was found to not reduce the feasibility or acceptability of autonomous operations. In the current experiment we focused on scenarios where the maneuvering space available to the pilot was greatly reduced by special-use airspace. We also considered the implications of a reduced lateral separation standard. In neither case was feasibility or acceptability to our subject pilots reduced. Of the three separation violations that occurred, one was a simulation artifact, and in the other two the minimal separation was only slightly less than the requirements.

It is clear that flight deck tools for autonomous aircraft operations must conform to the pilot's normal flight practices. In this experiment we have gained additional knowledge on how and when our current tools were useful and not useful. Both loss of separation cases occurred when the pilot attempted an altitude change without verifying there was sufficient separation from other traffic. This problem was also observed in previous work [5]. We at-

tribute this operational error to the tools not adequately accommodating the multiple ways a pilot may initiate a vertical maneuver, and to the spatial separation between the autoflight controls and the conflict prevention information. The presentation of conflict prevention information must be improved to eliminate these problems.

The pilots also frequently left the strategic mode for a more tactical mode of operation. There is a combination of reasons for this. One is that several pilots wished to resolve conflicts with a temporary altitude change instead of a lateral maneuver around the intruding aircraft. In the current prototype version of the Autonomous Operations Planner (AOP), strategic conflict resolutions are only available in the lateral plane. We are currently working on a vertical resolution capability to answer these concerns. The use of a predictable and trustworthy flight plan offers the greatest stability to the system; therefore, it is our goal to offer solutions that meet the pilot's objectives while maintaining the flight plan. To this end we are also expanding the capabilities of the AOP to better support the multitude of ways that pilot's fly their aircraft.

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Key Words

DAG-TM, Free Flight, conflict resolution, constrained airspace, autonomous operations, en route airspace

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Mr. Barhydt has a B.S. in Aerospace Engineering from the University of Colorado (1995) and an S.M. in Aeronautics and Astronautics from MIT (1997). He is an aerospace engineer at the NASA Langley Research Center, working on the Advanced Air Transportation Technologies project. He has experience in Flight Management System operations and has conducted experiments on the use of intent information on cockpit traffic displays. He is a certified instrument flight instructor and commercial pilot for single engine aircraft. He is also a member of RTCA Special Committee 186, Working Group 4 (Application Technical Requirements) and Working Group 6 (ADS-B MASPS Revision A).